Defense Threat Reduction Agency
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TECHNICAL REPORT

Towards Resilient Information-Aware Communication Networks

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February 2013

HDTRA1-09-1-0051

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14. ABSTRACT

Many communication networks today follow a distributed architecture, informed by a desire for immunity to attack by WMDs. However, the ``information architecture" of these networks is based on the assumption that information at one location is not replaceable by that somewhere else. In this project we do away with this assumption, embrace the duplicable nature of information, and view communication networks as distributed data bases that must maintain and serve information in spite of attack by WMDs. Our objective is to create algorithms and mechanisms that transmit ``high-value bits at high-speed" in a scalable and attack-resilient manner.

15. SUBJECT TERMS

Physical networks, peer-to-peer networking, robust information access, distributed optimization.

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CONVERSION TABLE

Conversion Factors for U.S. Customary to metric (SI) units of measurement.

MULTIPLY ⟶ BY ⟶ TO GET

TO GET ⟵ BY ⟵ DIVIDE

angstrom	1.000 000 x E -10	meters (m)
atmosphere (normal)	1.013 25 x E +2	kilo pascal (kPa)
bar	1.000 000 x E +2	kilo pascal (kPa)
barn	1.000 000 x E -28	meter^2 (m^2)
British thermal unit (thermochemical)	1.054 350 x E +3	joule (J)
calorie (thermochemical)	4.184 000	joule (J)
cal (thermochemical/cm^2)	4.184 000 x E -2	mega joule/m^2 (MJ/m^2)
curie	3.700 000 x E +1	*giga bacquerel (GBq)
degree (angle)	1.745 329 x E -2	radian (rad)
degree Fahrenheit	$t_k = (t^{o}f + 459.67)/1.8$	degree kelvin (K)
electron volt	1.602 19 x E -19	joule (J)
erg	1.000 000 x E -7	joule (J)
erg/second	1.000 000 x E -7	watt (W)
foot	3.048 000 x E -1	meter (m)
foot-pound-force	1.355 818	joule (J)
gallon (U.S. liquid)	3.785 412 x E -3	meter^3 (m^3)
inch	2.540 000 x E -2	meter (m)
jerk	1.000 000 x E +9	joule (J)
joule/kilogram (J/kg) radiation dose absorbed	1.000 000	Gray (Gy)
kilotons	4.183	terajoules
kip (1000 lbf)	4.448 222 x E +3	newton (N)
kip/inch^2 (ksi)	6.894 757 x E +3	kilo pascal (kPa)
ktap	1.000 000 x E +2	newton-second/m^2 (N-s/m^2)
micron	1.000 000 x E -6	meter (m)
mil	2.540 000 x E -5	meter (m)
mile (international)	1.609 344 x E +3	meter (m)
ounce	2.834 952 x E -2	kilogram (kg)
pound-force (lbs avoirdupois)	4.448 222	newton (N)
pound-force inch	1.129 848 x E -1	newton-meter (N-m)
pound-force/inch	1.751 268 x E +2	newton/meter (N/m)
pound-force/foot^2	4.788 026 x E -2	kilo pascal (kPa)
pound-force/inch^2 (psi)	6.894 757	kilo pascal (kPa)
pound-mass (lbm avoirdupois)	4.535 924 x E -1	kilogram (kg)
pound-mass-foot^2 (moment of inertia)	4.214 011 x E -2	kilogram-meter^2 (kg-m^2)
pound-mass/foot^3	1.601 846 x E +1	kilogram-meter^3 (kg/m^3)
rad (radiation dose absorbed)	1.000 000 x E -2	**Gray (Gy)
roentgen	2.579 760 x E -4	coulomb/kilogram (C/kg)
shake	1.000 000 x E -8	second (s)
slug	1.459 390 x E +1	kilogram (kg)
torr (mm Hg, 0^0 C)	1.333 22 x E -1	kilo pascal (kPa)

*The bacquerel (Bq) is the SI unit of radioactivity; 1 Bq = 1 event/s.

**The Gray (GY) is the SI unit of absorbed radiation.

1 Accomplishments

1.1 Major Goals

The objective of this project was to ensure communication of valuable information under highly resource constrained environments caused by WMD attack. Further, limited wireless spectrum together with interference and fading pose significant challenges for network designers. The major goal of this project was to explore algorithms and mechanisms to ensure robust availability of information under such conditions.

1.2 Accomplishments under these goals

1.2.1 Activities

1. Designing Network coding based routing in robust ad-hoc wireless networks.
2. Designing a content-aware routing, placement and eviction algorithm for CDNs under resource constrained situations.
3. Understanding protocol selection based on heterogeneous application requirements.
4. Designing algorithms for delay sensitive wireless content streaming.

1.2.2 Objectives

The main objective was to explore content distribution in wired and wireless networks under resource constrained situations. The specific objectives over the past year was:

1. To study coordination to save energy using network coding in multi-hop wireless networks
2. To design algorithms for content caching and dissemination.
3. To study the use of peer-to-peer technology in providing guarantees for on-time content delivery in streaming systems.

1.2.3 Results

State Space Augmentation in Potential Games

In [C6], we introduced the concept of state space augmentation as a solution to coordination problems in wireless networks. Consider the wireless network coding scheme in Figure 1(a). Here, wireless nodes 1 and 2 need to exchange packets x_1 and x_2 through a relay node (node 3). A simple *store-and-forward* approach needs four transmissions. However, a network coding solution uses a *store-code-and-forward* approach in which the two packets x_1 and x_2 are combined by means of a bitwise XOR operation at the relay and broadcast to nodes 1 and 2. Nodes 1 and 2 can then decode this packet to obtain the packets that they need.

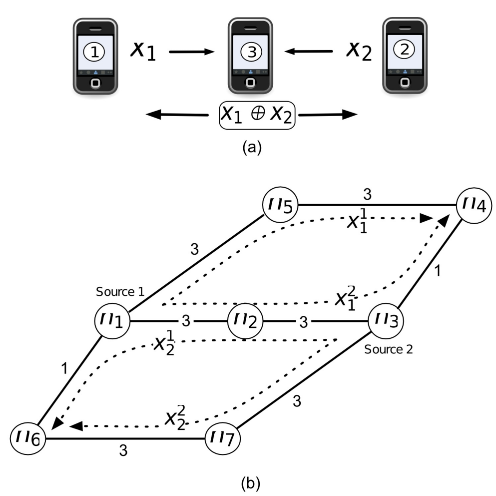

Figure 1: **A network coding game.**

Now, consider the scenario depicted in Figure 1(b). We have two sources with equal traffic, each of which is aware of two paths leading to its destination. Each has one path that costs 6 units, while the other costs 7 units. If both flows use their individually cheaper paths, the total cost is 12 units. However, if both use the more expensive path, since network coding is possible at node n_2, the total cost is reduced to 11 units. We see that there is a dilemma here—savings can only be obtained if there is sufficient bi-directional traffic on (n_1, n_2, n_3). The first mover in this case is clearly at a disadvantage as it essentially creates the route that the other can piggyback upon (in a reverse direction).

The system can be represented as a potential game with the potential function being the total cost given the traffic splits. However, if each source attempts to learn its optimal traffic split based on the cost that it observes, it could easily choose an inefficient solution. The inefficiency was characterized as being large in some networks. However, we showed in [C6] that by adding an agent (with only local information) at node n_2 that provides rebates for using the network coded path, the potential function seen by the original agents can be altered in such a way that the equilibrium is efficient. These augmented agents at the coding nodes use their own learning dynamics (gradient-based, in this case) to decide how to modify the potential function at each time. In spite of the rebates, the overall cost is not increased but is merely redistributed in the system. The result is valid for general topologies, with each augmented agent taking local decisions to offer rebates, and learning whether to increase or decrease the rebate based on the observed impact. We developed the idea still further to understand coordination ideas in settings where each player has different protocols to choose from [C1].

Demand inference using request queue information.

A simple abstraction of a content distribution network (CDN) is illustrated in Figure 2, taken from the PI's recent work [C2,C3,C7]. It consists of frontend servers[1] (denoted by 'F') that aggregate queries arising in different geographical locations, and route each query (query types indicated by numbers) to an appropriate backend cache indicated by a 'B'. Multiple caches could potentially serve each query, and the frontend has to take a decision on which to pick. For each request that is routed to a cache, a corresponding file is transmitted back to the requesting source across links of finite capacity. Caches are of finite size, and the content can be refreshed periodically from a media vault, with the frequency of refresh representing the cost of access.

The objective is to design policies for request routing, content placement and content eviction with the goal of small user delays. Stable policies ensure the finiteness of the request queues, while good polices also lead to short queue lengths. Thus, request routing and content placement should be such that the system is stable if

$$\sum_{\forall c} \lambda_s^c < \sum_{\forall d} C_{sd}, \qquad (1)$$

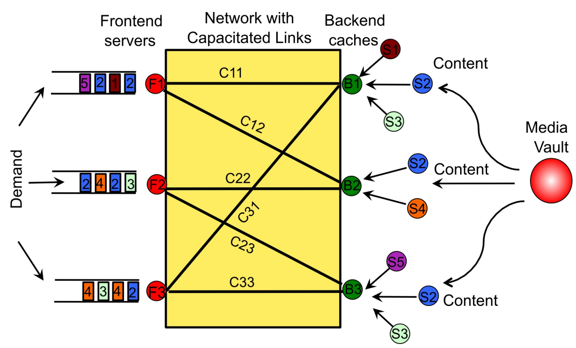

Figure 2: **Query assignment in a CDN. Queries may have strict deadlines.**

where λ_s^c is the arrival rate of requests for content c at frontend s, and C_{sd} is capacity constraint between frontend s and cache d. Suppose that each frontend divides up requests into different queues based on the content requests, *i.e.*, we have request queue length $q_s^c[k]$ at source s for content type c at time k. Note that these queues are merely counters, and do not have real packets. Since the CDN does not know λ_s^c, it needs to infer the appropriate request routing and content placement using request queue length information. We showed in [C2,C3] that during the times at which content refreshing is allowed, the media vault should follow a *maximum weight schedule* (where the weight of any link in the schedule is the product $q_s^c[k]C_{sd}$) coupled with *minimum weight eviction*. At times when refreshing is not allowed, the schedule is simply a maximum weight schedule *subject to the content present* in the cache. We showed using Foster-Lyapunov type ideas that such a policy stabilizes the system (*i.e.*, implicitly determines the necessary content placement) and leads to short queue lengths (and hence users see small delays).

Minimum Buffer Size Requirements in Large P2P Streaming Networks

The predominant application in future networks will be real-time content streaming. We explore the use of peer-to-peer (P2P) approaches for scalable and robust content delivery [J1,J3,C4,C5]. In such P2P streaming systems, each peer maintains a playout buffer of content chunks which it attempts to fill by contacting other peers in the network. The objective is to ensure that the chunk to be played out is available

[1]These are Web servers that perform http or DNS-based redirection of the queries.

with high probability while keeping the buffer size small. A small playout buffer means that the playout delay is small. Thus, the objective is to study the tradeoff between two measures of QoS, chunk playout rate and delay. A *policy* is a rule that suggests which chunks should be requested by the peer from other peers.

In [J1], we considered a system consisting of M users who are all simultaneously interested in a real-time content stream generated by a server. The stream consists of chunks with one new chunk generated at each discrete time instant, and the server selects one peer at random for each new chunk. Peers obtain chunks either if they are selected by the server, or by full-mesh P2P with random peer selection. Peers maintain a buffer of size m, with the chunk in the mth location played out at each time instant if available. We have a target of skip-free playout probability of q over all peers.

We present an analytical characterization of the scaling of required buffer size m with M and q under different policies. The main results of of our analysis are summarized below:

- We consider the *rarest-first policy* wherein priority is given to the chunks farthest from playout. In other words, a peer picks that chunk in the difference set with its selected peer that is closest to the first buffer position. We show that given any target probability $0.5 < q \leq 1$, the buffer size to attain this target probability with the rarest-first policy scales approximately as

$$\log(M) + \log(2q - 1) + \frac{1}{2(1-q)}.$$

- We then consider the *greedy policy* wherein priority is given to the chunks closest to playout. Thus, a peer picks that chunk in the difference set with his selected peer that is closest to the mth buffer position. We show that given any target probability $q \geq \frac{1}{M}$, the buffer size to attain this target probability with the greedy policy approximately scales in a similar fashion as

$$\log(M) + \log(q) + \frac{1}{1 - q + \frac{2}{M}}.$$

- We study a *hybrid policy* h_ϵ which combines the greedy and the rarest-first policies. The policy uses rarest-first up to a buffer position where the probability of occupancy is greater than ϵ, and switches to using the greedy policy from there on. For this policy, we show that there exist constants a_ϵ and a_{ϵ,ϵ_2}, independent of M and q, such that, if the buffer size m satisfies

$$m \geq a_\epsilon \log(M) + a_{\epsilon,\epsilon_2} \log\left(\frac{1}{1-q}\right),$$

  then the skip-free playout probability $p_{(h_\epsilon,m)}(m) \geq q$. Thus, the buffer size required by this policy is less than that required by either the rarest-first or greedy policies in an order sense, and is asymptotically optimal.

1.2.4 Key Outcomes

1. Development of a new class of coordination using state space augmentation in potential games. The idea is likely to have an impact on a large class of coordination games. Applied the idea to multipath network coding for minimum cost routing in networks, and illustrated how it can result in the lowest cost (in terms of energy) solution.

2. Development of traffic management, caching, and eviction policies for elastic and inelastic traffic conditions and constrained resource situations. This idea is also relevant to data center management at high load situations, and Google Inc. has shown interest in adopting similar algorithms.

1.3 Training and Professional Development

1.3.1 Training

Four PhD students were funded in part by this grant. One is graduating in September 2011, while two more will graduate in the next year. the students have been trained to design and develop robust networking algorithms, and have benefited by exposure to ideas of severely resource restricted environments and catastrophic failure situations.

1.3.2 Professional development

The PI visited U Colorado at Boulder in June 2010 for ten days. Gave talks on augmented state space potential games, and collaborated with Dr. Jason Marden (Dept. of ECE) on generalizing the idea to a larger space of problems. The PI spent six weeks at California Institute of Technology in May-June 2011, hosted by Prof. Adam Wierman (dept. of CS). Worked on using network coding for high speed and low energy data communication.

1.4 Dissemination

1.4.1 Within research community

1. Designing Network coding based routing in robust ad-hoc wireless networks. Presentation at Caltech 2011.
2. Designing a content-aware routing, placement and eviction algorithm for CDNs under resource constrained situations. Presentation at IEEE Infocom 2011, Stanford 2011.
3. Understanding protocol selection based on heterogeneous application requirements. Presentation at IEEE Infocom 2011.
4. Designing algorithms for delay sensitive wireless content streaming. Presentation at IEEE WiOpt 2011.

1.4.2 Outreach

1. Gave seminars on computer networking at"Discover ECE" 2009, 2010, 2011 aimed at helping admitted high school students to decide their choice of ECE stream. Explained the basic ideas underlying computer networks, the need for robustness, and possible threats.
2. Mentored a group of high school students as part of "ECE Unplugged" 2009, 2010. The purpose was to develop interest in ECE as a career choice by introducing the students to basic ECE concepts as well as hands-on experience. Students mentored by PI Shakkottai built simple electronic circuits, and were familiarized with Internet architecture ideas and networking concepts. Also illustrated the idea of peer-to-peer, the need for reliability, and the use of such systems under disaster situations.

1.5 Plan For Next Reporting Period

No change.

2 Products

2.1 Publications

2.1.1 Journal Publications

J1 S. Shakkottai, R. Srikant and L.Ying, "The asymptotic behavior of minimum buffer size requirements in large P2P streaming networks", *To appear in IEEE Journal on Selected Areas in Communication*.

J2 P. Parag, S. Shakkottai and J-F. Chamberland, "Value-Aware Resource Allocation for Service Guarantees in Networks", *To appear in IEEE Journal on Selected Areas in Communication*.

J3 A. ParandehGheibi, M. Médard, A. Ozdaglar and S. Shakkottai, "Avoiding Interruptions - a QoE Reliability Function for Streaming Media Applications", *To appear in IEEE Journal on Selected Areas in Communication*.

2.1.2 Books

B1 S. Shakkottai and A. Eryilmaz, "Optimization and Control of Communication Networks", appeared as a chapter in *The Control Handbook*, edited by William Levine, CRC-Press, New York, 2010.

2.1.3 Conferences and other presentations

C1 V. Ramaswamy, D. Choudhury and S. Shakkottai, "Which Protocol? Mutual Interaction of Heterogeneous Congestion Controllers" in *IEEE INFOCOM 2011*, Shanghai, April 2011.

C2 M. Amble, P. Parag, S. Shakkottai and L. Ying, "Content-Aware Caching and Traffic Management in Content Distribution Networks" in *IEEE INFOCOM 2011*, Shanghai, April 2011.

C3 N. Abedini and S. Shakkottai, "Content Caching and Scheduling in Wireless Broadcast Networks with Elastic and Inelastic Traffic" in IEEE WiOpt '11, Princeton, NJ, May 2011.

C4 A. ParandehGheibi, M. Medard, A. Ozdaglar and S. Shakkottai, "Access-Network Association Policies for Media Streaming in Heterogeneous Environments" in the IEEE Conference on Decision and Control *CDC*, Atlanta, GA, December 2010.

C5 A. ParandehGheibi, M. Médard, S. Shakkottai and A. Ozdaglar, "Avoiding Interruptions - QoE Tradeoffs in Block-coded Streaming Media Applications" in ISIT 2010, Austin, TX, June 2010.

C6 "'Multipath Wireless Network Coding: A Population Game Perspective," Seminar at California Institute of Technology, Pasadena, CA, April 2011.

C7 "'Content-Aware Caching and Traffic Management in Content Distribution Networks," Seminar at Stanford University, Stanford, CA, May 2011.

2.2 Websites for dissemination

1. IEEE Explore: `http://ieeexplore.ieee.org/`.
2. PI's personal webpage: `http://www.ece.tamu.edu/~sshakkot`

2.3 Technologies

No technologies beyond algorithms described in accomplishments.

2.4 Inventions, patent applications, and/or licenses

None.

2.5 Other products

None.

3 Participants& Other Collaborating Organizations

3.1 Individuals that worked on the project

Senior Personnel

Name: Shakkottai, Srinivas
Worked for more than 160 Hours: Yes
Contribution to Project: Srinivas Shakkottai is the PI of this project. He supervised all the students, and was directly involved in design, and validation of the algorithms proposed.

Graduate Students

Name: Ramaswamy, Vinod
Worked for more than 160 Hours: Yes
Contribution to Project: Vinod worked on game-based control systems in the context of multi-hop wireless networks. His principal contribution was in the design of augmented state-space controllers for network coding, and understanding protocol interaction.

Name: Abedini, Navid
Worked for more than 160 Hours: Yes
Contribution to Project: Navid worked on robust content distribution networks. He designed algorithms for content streaming with strict delay guarantees.

Name: Manjrekar, Mayank
Worked for more than 160 Hours: Yes
Contribution to Project: Mayank worked on network coding in wireless peer-to-peer networks, and on interface management to do so at minimum power.

Name: Parag, Parimal
Worked for more than 160 Hours: Yes
Contribution to Project: Parimal worked on aspects of content distribution networks in a case of joint caching, traffic management, and cache eviction.

3.2 Other organizations involved as partners

University of Illinois at Urbana-Champaign
Collaborated with Prof. Rayadurgam Srikant (Dept. of ECE).

Iowa State University
Collaborated with Prof. Lei Ying (Dep. of ECE).

Massachusetts Institute of Technology
Collaborated with Prof. Asuman Ozdaglar and Prof. Muriel Medard (Dept. of EECS).

3.3 Other collaborators or contacts

None.

4 Impact

4.1 Impact on the development of the principal discipline(s) of the project

The idea of state space augmentation in potential games is likely to be useful in coordination in several different coordination problem environments. The ideas on content caching has been well received by both academia and industry, resulting in Google Faculty Research award for the PI, and inquiries for collaboration from Akamai Network.

4.2 Impact on other disciplines

Game-based control systems are of use in multi-agent systems in a variety of different fields, including transportation networks, cyber physical systems such as UAV networks, besides communication networks.

4.3 Impact on the development of human resources

- The project provided opportunities for research for graduate students. The PI taught courses on Design and Analysis of Communication Networks and also supervised students in a Smart Phone laboratory during this period. Both the course and lab experience focused in part on reliability, robustness, and fault tolerance during failure of systems.
- One student completed his PhD thesis while funded in part by this project. Two students have reached the stage of their preliminary exam, and are expected to receive PhDs in the next year.
- Under represented students (female, Hispanic, and African American) worked and continue to obtain valuable experience in the smart phone lab, advised by the PI.
- ECEN 750 Design and Analysis of Communication Networks (Spring 2010), a graduate course that deals with resource allocation in networks. Introduced some ideas of scaling in multihop wireless networks, and robustness. ECEN 489 Networks and Networking (Fall 2010), undergraduate course that deals with network formation, search and social networks. Introduced ideas of k-connected graphs, reliability to failure, and the value of a small number of long links for low path lengths.

4.4 Impact on technology transfer

The algorithms on content distribution were of interest to Google Inc., and the PI received a Google Faculty Research Award based on the idea.

4.5 Impact on society beyond science and technology

None recorded.

5 Changes

No changes.

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